FINAL REPORT

to

THE OFFICE OF NAVAL RESEARCH

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Grant Title:

Theoretical and Modeling Studies of The Marine Planetary Boundary Layer

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SCIENTIFIC BACKGROUND AND RESEARCH GOALS:

We do not currently understand what determines the fractional cloudiness in partly cloudy boundary layers, how it is influenced by cloud-top entrainment instability (Randall, 1980), or what controls the transition from stratocumulus to cumulus conditions. These questions have a direct bearing on the radiation budget at both the top the atmosphere and the sea surface, and also on the entrainment rate (Randall, 1987).

The importance of boundary-layer clouds stems, to a large extent, from their powerful influence on the net radiation at the sea surface. They block incident solar radiation (with albedoes up to about 50%) and at the same time emit downward strongly in the infrared. Their net effect on the surface energy budget is believed to be a strong reduction in the energy absorbed by the ocean (e.g. Esbensen and Kushnir, 1981). Despite the obvious importance of this effect for the thermal structure of the upper ocean, very little is known about the coupling between the ocean mixed layer with boundary layer clouds. The coupling can work in both directions; the sea surface temperature strongly influences the type and amount of boundary-layer cloud, while large cloud amounts are favored where the sea surface temperature is low (e.g., Hanson, 1990).

Modeling studies of boundary-layer clouds date back to the work of Lilly (1968), who proposed a highly innovative yet simple model of the cloud-capped atmospheric boundary layer. Although his model allowed only fully overcast or completely cloud-free boundary layers, he did point out the possibility that the cloudiness could be reduced by various processes, including what has come to be called "cloud-top entrainment instability" (CTEI). Lilly also recognized that the cloud amount tends to be larger over cold water, and smaller over warm water.

Kraus and Leslie (1982) combined an atmospheric boundary-layer model similar to Lilly's with a simple upper ocean model. The joint evolution of the lower atmosphere and upper ocean was predicted by the model. The cloudiness predicted by the atmospheric model modulated the

insolation of the upper ocean, thus regulating the sea surface temperature. Kraus and Leslie pointed out that stratus clouds tend to keep the sea surface cool by blocking solar radiation, while at the same time cool sea surface temperatures are favorable for the formation and persistence of stratus clouds. They recognized the importance of increasing sea surface temperatures for reducing the cloudiness, although their model was not able to predict fractional cloud amounts.

Randall (1980, 1987, 1989) has recently developed a simple atmospheric boundary layer model capable of predicting the boundary-layer cloud amount. This opened up the possibility of extending the study of Kraus and Leslie, by constructing a coupled ocean-atmosphere model in which the cloud amount varies dynamically according to the predicted sea surface temperature (and other factors). Such a model can be used to study the transition from stratus to shallow cumulus clouds, and the role of air-sea interactions in determining the time and location of such transitions.

To provide the data needed to analyze these processes, the Office of Naval Research is sponsoring ASTEX, the Atlantic Stratocumulus Transition Experiment, which will be conducted near the Azores in the summer of 1992. The data that ASTEX collects will be particularly useful if they can be applied to test suitable theoretical and numerical models of the marine boundary layer. A primary goal of this project has been to develop models that can be tested in ASTEX. A further goal has been to participate in the ASTEX planning process. Our objectives are to produce an extensive set of theoretical and numerical results,leading to better physical understanding of the cloudy marine boundary layer and providing a theoretical basis for the planning and execution of ASTEX (the Atlantic Stratocumulus Transition Experiment). In particular, we have worked:

- To gain an improved theoretical understanding of and predictive capability for partly cloudy boundary layers, and to test these ideas against data acquired in the field.
- To investigate the role of air-sea interactions in regulating cloud amount in the marine boundary layer.

SCIENTIFIC RESULTS:

Marine Boundary Layer Model Development

Randall et al. (1992) have developed a new type of boundary-layer model that combines second-order closure with a bulk representation of the vertical structure. The boundary-layer depth and turbulence kinetic energy (TKE) are prognostically determined. The large turbulent eddies that are primarily responsible for the fluxes are modeled as convective circulations, with ascending and descending branches. The interior of the boundary layer is bounded above by a thin entrainment layer and below by a thin ventilation layer. Conservative variables such as the equivalent potential temperature have quadratic profiles in the interior. Convective circulations occur, with rising branches occupying fractional area s, which is predicted by the model. The upper ocean is represented by a mixed layer whose depth can be either fixed or variable, depending on the objectives of the numerical experiment being conducted.

The new theoretical model has been developed and used to derive the scientific results described below. The same model is being tested as a numerical prediction tool. We have completed extensive tests of the model against two data sources:

- observations collected by tethered balloon on San Nicolas Island during FIRE 1987; and
- large-eddy simulations performed by Chin-Hoh Moeng of NCAR.

We have also used both data sources to evaluate certain parameters that appear in the model. This work has been accepted for publication in the *Journal of the Atmospheric Sciences*. In addition, we have coupled the boundary-layer model with simple upper ocean and sea ice models. We are currently investigating the possiblity of multiple equilibria of the ocean - ice - atmosphere system, made possible by the boundary-layer clouds which, when present, strongly affect the energy budget of the sea ice.

Fig. 1 shows an example of results obtained with this model, and a comparison with large-eddy simulations.

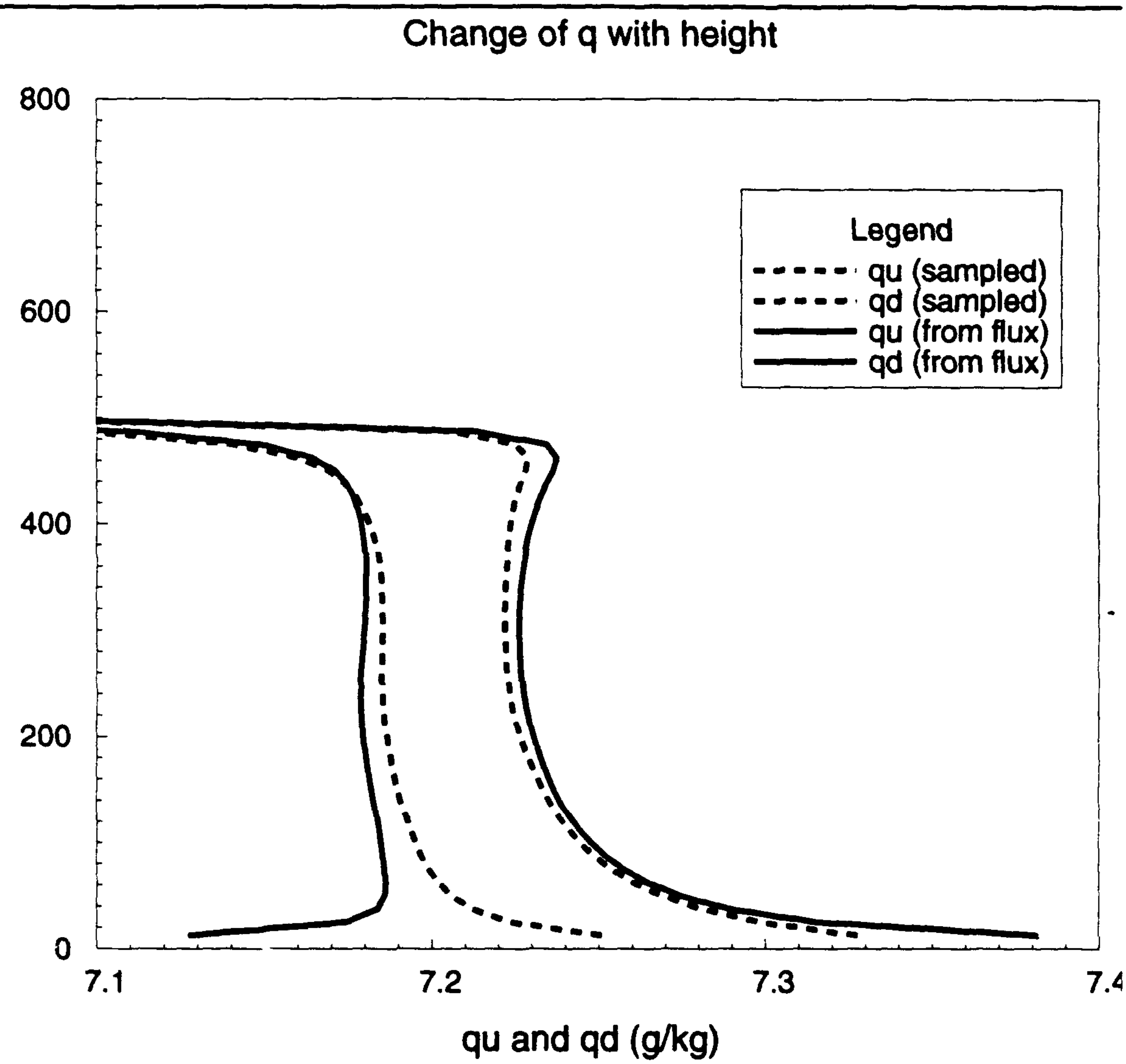

Figure 1: Moisture profiles in updrafts (qu) and downdrafts (qd) as simulated by a large-eddy model (dashed lines) and as predicted, based on fluxe profiles, by the bulk boundary layer model developed here. The larger values are for the moist updrafts, and the smaller values are for the dry downdrafts.

The model has successfully predicted the vertical profiles of the updraft and downdraft properties

(in this, case, mixing ratio) except that the downdrafts very close to the surface are predicted to be drier than the large-eddy simulation predicted.

The new boundary layer model makes a number of new predictions concerning the convective turbulence of cloudy layers. For the special case of a well-mixed layer, it predicts that the fractional area covered by rising motion is near 1/2, and that dissipation in the interior of the layer is weak. When the dissipation is weak and the fractional area covered by rising motion is small, the model gives the "compensating subsidence -- detrainment" relationship that has become familiar in cumulus parameterization theories. When the dissipation is strong and the fractional area covered by rising motion is near 1/2, the model gives downgradient diffusion. For the shallow cumulus regime, the model predicts that the fractional area covered by rising motion is smaller for the case of large-scale rising motion than for large-scale sinking motion. These model predictions are consistent with a variety of observed balances in convective layers. The model is based on various assumptions which have been tested against data. A particularly interesting new result is the prediction that potential temperature should increase upward in a convective layer, while mixing ratio should decrease upward. Both predictions are consistent with observations.

These results provide a very useful dynamical interpolation between the "compensating subsidence" and "mixing length" regimes. They tie together ideas that were previously thought to be unrelated. This unification opens the door to new predictive tools that are both simpler and more powerful that those in current use. These ideas have already been useful in the scientific planning of ASTEX. In addition, we have demonstrated that the predictions of the model are consistent with both observations and LES results. This provides a basis for confidence in both the simple model and the large-eddy model.

It is our intention to run the model in the field, in “real time” numerical experiments during ASTEX.

Investigation of physical processes in the marine boundary layer

In a further investigation of the effects of various physical processes on the turbulence in the cloud-topped boundary layer (Moeng et al., 1992), we analyzed three large-eddy simulations of idealized stratus-topped boundary layers to study four physical processes: cloud-top longwave radiative cooling, entrainment, surface heating, and latent heating. Within highly turbulent, convective boundary layers, turbulent circulations can be well characterized by the updraft and downdraft branches, and turbulent transports of heat and moisture can be well described by the differences between these two branches.

We conditionally sampled the large-eddy simulation field, and investigated the contribution of each process to the mean-field differences between updrafts and downdrafts. Based on the results of this analysis, we process-partitioned the total heat flux and the total moisture flux, which are linear in height for a homogeneous, quasi-steady state. The heat and moisture fluxes obtained by combining the partitioning fluxes agree quite well with those obtained directly from the large-eddy simulations.

Fig.2 shows that the updraft-downdraft model succeeds very well in reproducing the large-eddy simulated flux profiles for a two different cases, including the clear convective boundary layer and a nocturnal cloud-topped boundary layer. The agreement is amazingly good, and is equally good in two more cases that are not shown here.

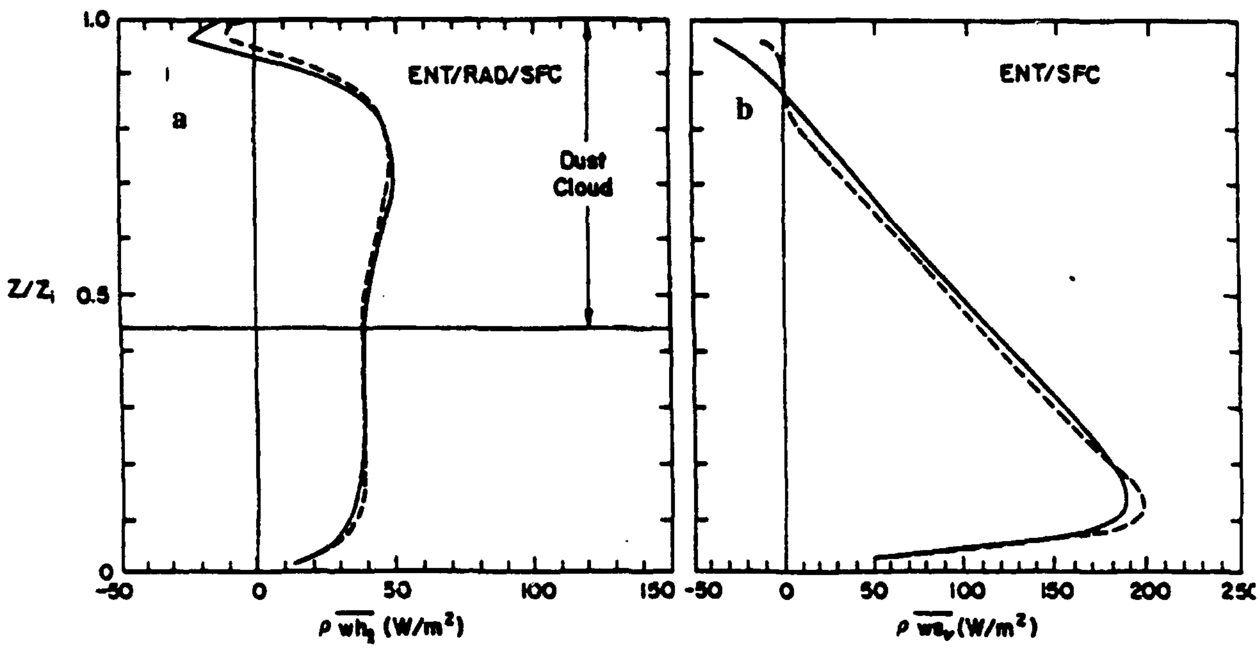

Figure 2: Flux profiles obtained through large-eddy simulation (solid curves) and as predicted by the updraft-downdraft model (dashed curves), for two different physical situations: a) a noctural marine boundary layer; b) a clear convective boundary layer.

Coupled ocean-atmosphere model development

In addition, we have constructed a coupled ocean-atmosphere model which can be used to study the interactions between boundary-layer clouds and the sea surface temperature. The model currently is one-dimensional, and has a simple Richardson-number dependent mixing in both the atmosphere and ocean. Mean vertical motion and geostrophic shear can be prescribed for both the atmosphere and ocean. It is our intention to add sea ice as an option in the model, in the future.

Our first tests were for cloud-free cases. These were used essentially for debugging the mixing and vertical advection codes. An example is shown in Fig. 3. Here we performed two one-day simulations.

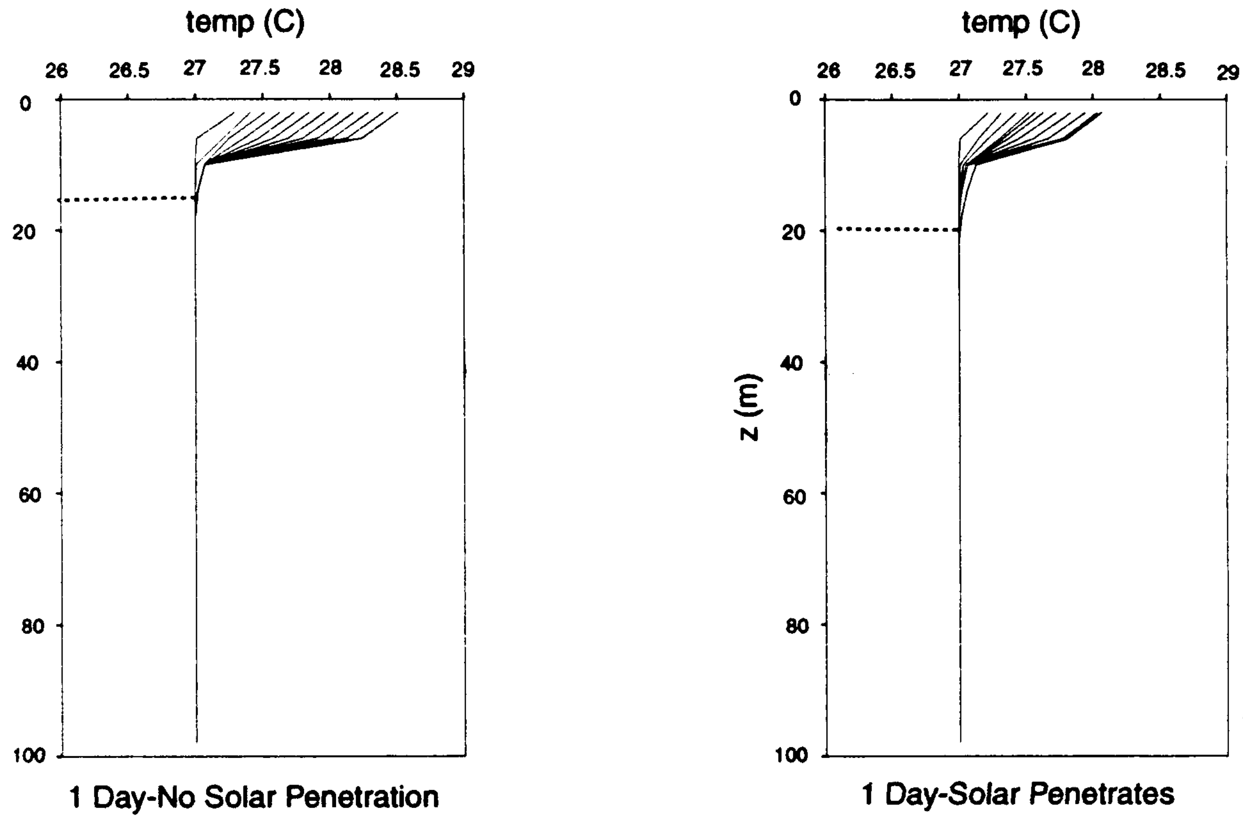

Figure 3: Results from a test of the coupled ocean-atmosphere model. In the left panel, solar radiation is assumed to be absorbed completely in the top layer of the model. In the right panel it is allowed to penetrate.

In the first, solar radiation was assumed to be deposited completely in the top layer of the ocean model, while in the second the solar radiation was allowed to penetrate through several layers. The results show greater surface warming in the absence of solar penetration, and greater warming at depth when penetration occurs.

We are currently testing the model with a "dry cloud" that produces radiative cooling but no latent heat effects. This problem was first studied by Lilly (1968) and has proven itself to be a valuable testbed. We plan to continue this model development work by incorporating latent heat

effects, and adding a sea ice parameterization.

References

Esbensen, S. K., and Y. Kushnir, 1981: The heat budget of the global ocean: An atlas based on estimates from surface marine observations. *Climatic Research Institute Report No. 29,* Oregon State University, Corvallis, Oregon 97331.

Fiedler, B. H., 1983: The mesoscale stability of entrainment into cloud-topped mixed layers. *J. Atmos. Sci.*, **40**, 92-101.

Hanson, H. P., 1990: Marine stratocumulus climatologies. *International J. of Climatology*, **11**, 147 - 164.

Kraus, E. B., and L. D. Leslie, 1982: The interactive evolution of the oceanic and atmospheric boundary layers in the source regions of the trades. *J.Atmos. Sci.*, **39**, 2760-2772.

Lilly, D. K., 1968: Models of cloud-topped mixed layers under a strong inversion. *Quart. J. Roy. Meteor. Soc.*, **94**, 292-309.

Price, J. F., and R. A. Weller, 1986: Diurnal cycling: Observations and models of the upper ocean response to diurnal heating, cooling, and wind mixing. *J. Geophys. Res.*, **91**, 8411-8427.

Randall, D. A., 1980: Conditional instability of the first kind, upside-down. *J. Atmos. Sci.*, **37**, 125-130.

Randall, D. A., and M. J. Suarez, 1984: On the dynamics of stratocumulus formation and dissipation. *J. Atmos. Sci.*, **41**, 3052-3057.

Randall, D. A., 1987: On the turbulent fluxes of liquid water and buoyancy in partly cloudy layers. *J. Atmos. Sci.*, **44**, 850-858.

Randall, D. A., 1989: A unified view of convective transports by stratocumulus clouds, shallow cumulus clouds, and deep convection. Paper presented at the *FIRE Science Team Meeting,* July 10-14, 1989, Monterey, California.

Turton, J. D., and S. Nicholls, 1987: A study of the diurnal variation of stratocumulus using a multiple mixed layer model. *Quart. J. Roy. Meteor. Soc.*, **113**, 969-1010.

PUBLICATIONS FROM ONR-SPONSORED WORK:

Refereed publications:

Randall, D. A., Q. Shao, and C.-H. Moeng 1992: A Second-Order Bulk Boundary-Layer Model. Accepted for publication in the *Journal of the Atmospheric Sciences.*

Moeng, C.-H., S. Shen, and D. A. Randall, 1992: Physical Processes within the Nocturnal Stratus-Topped Boundary Layer. Accepted for publication in the *Journal of the Atmospheric Sciences.*

Refereed publications in preparation:

Randall, D. A., Q. Shao, and C.-H. Moeng 1992: Mixing Processes in the Entrainment and Ventilation Layers. In preparation for the *Journal of the Atmospheric Sciences.*

Technical reports:

Randall, D. A., and Q. Shao, 1990: Formulation of a bulk boundary layer model with partial mixing and partial cloudiness. *Atmospheric Science Paper No. 460,* Colorado State University, 47 pp.

Invited conference papers:

Randall, D. A., 1989: Evidence for the Sensitivity of Large-Scale Models to Boundary-Layer Parameterizations. Paper presented at the *Symposium on Boundary-Layer Parameterization and Larger-Scale Models,* IAMAP-89, August 9, 1989, Reading, England.

Randall, D. A., 1989: What Should a Boundary-Layer Parameterization for Climate Models Include? Paper presented at the *Workshop on Boundary-Layer Parameterization for Large-Scale Models of the World Climate Research Program,* August 14-15, 1989, Reading, England.

Contributed conference papers:

Randall, D. A., 1989: Cloudtop Entrainment Instability: Current Knowledge and Key Questions. Paper presented at the *ASTEX Planning Meeting,* July 13-14, 1989, Monterey, California.

Randall, D. A., 1989: A Unified View of Convective Transports by Stratocumulus Clouds, Shallow Cumulus Clouds, and Deep Convection. Paper presented at the *FIRE Science Team Meeting,* July 10-14, 1989, Monterey, California.

Randall, D. A., and Q. Shao, 1990: A Physically Based Fractional Cloudiness Parameterization. Paper presented at the *Conference on Cloud Physics of the American Meteorological Society,* July 24-27, 1990, San Francisco, California.

Jensen, T. G., D. A. Randall, and D. A. Dazlich, 1991: Coupling of a Simple Thermodynamic Ocean Mixed Layer and Sea Ice Model to the CSU General Circulation Model. Paper presented at the *Fifth Conference on Climate Variations of the American Meteorological Society*, Denver, Colorado.

Shao, Q., and D. A. Randall, 1991: A New Planetary Boundary Layer Parameterization With Partial Mixing and Partial Cloudiness. Paper presented at the *Ninth Conference on Numerical Weather Prediction of the American Meteorological Society*, Denver, Colorado.

Patents filed:

NONE

Patents granted:

NONE

Honors/Awards/Prizes for grant employees:

Dean's Council Award, College of Engineering, Colorado StateUniversity, 1991.

Graduate students and post-docs supported at least 25% on this grant:

Graduate students 1

Post-docs 1

Graduate student female 1

Post-doc female 0

Graduate student minority 0

Post-doc minority 0

Graduate student Asian 1

Post-doc Asian 0